JPL NO. 9950-560

DRL No. 157
DRD No. SE-3
Item #6

TME 3110
DOE/JPL 955909-81/2
Distribution Category UC-63

LOW COST SOLAR ARRAY PROJECT

PRODUCTION PROCESS AND EQUIPMENT TASK

A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

QUARTERLY REPORT NO. 2

March 1, 1981 to May 31, 1981

CONTRACT NO. 955909

The JPL Low-Cost Silicon Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

Advanced Energy Systems Division
WESTINGHOUSE ELECTRIC CORPORATION
P. O. Box 10864
Pittsburgh, Pennsylvania 15236

LOW COST SOLAR ARRAY PROJECT
Production Process and Equipment Task

A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

QUARTERLY REPORT NO. 2
March 1, 1981 to May 31, 1981

Contract No. 955909

The JPL Low-Cost Silicon Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

Approved:

C. M. Rose

C. M. Rose, Project Manager
Photovoltaic Components

Advanced Energy Systems Division
WESTINGHOUSE ELECTRIC CORPORATION
P. O. Box 10864
Pittsburgh, Pennsylvania 15236

TECHNICAL CONTENT STATEMENT

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. CONTRACT GOALS AND OBJECTIVES

The objective of this contract is to demonstrate technical readiness for the production of photovoltaic modules designed to meet all specifications described in JPL Document 5101-138 and fabricated using single crystal silicon dendritic web sheet material. This demonstration of technical readiness will be accomplished by:

A. The selection, design, and implementation of a solar cell and photovoltaic module process sequence in a Module Experimental Process System Development Unit (MEPSDU),

B. Demonstration runs of the MEPSDU in which 240 modules will be produced,

C. Passing of acceptance and qualification tests by modules produced during the demonstration runs, and

D. Achievement of a 1986 module FOB price of 70¢ or less per watt peak in 1980 dollars as calculated by SAMIS using cost data generated during completion of the demonstration runs (Item B, above).

2. SUMMARY

Work on the Westinghouse MEPSDU contract was initiated on November 26, 1980. This report describes work performed during the second three-month period of the contract (March 1, 1980, through May 31, 1981) and outlines plans for the third quarter.

Work in the second quarter was initiated by a Preliminary Design Review (PDR) meeting held at JPL on March 4 and 5.

Module design work during this quarter resulted in several major modifications to the design presented at the PDR and described in the previous quarterly progress report. The frame was deleted in favor of a "frameless" design which will provide a substantially improved cell packing factor. Also, a modification in the cell series/parallel electrical interconnect configuration will eliminate potential shaded cell damage resulting from operation into a short circuit.

Substantial engineering effort was completed in refining the baseline process sequence defined for the Westinghouse MEPSDU. Equipment design and specification work was completed, albeit at a slower rate than originally planned due to reduced spending directions.

SAMICS cost analysis work was accelerated during this quarter. Format A's were prepared, and computer simulations completed on our terminal.

Design work at Kulicke and Soffa on the automated cell interconnect station proceeded as scheduled and was focused on bond technique selection experiments.

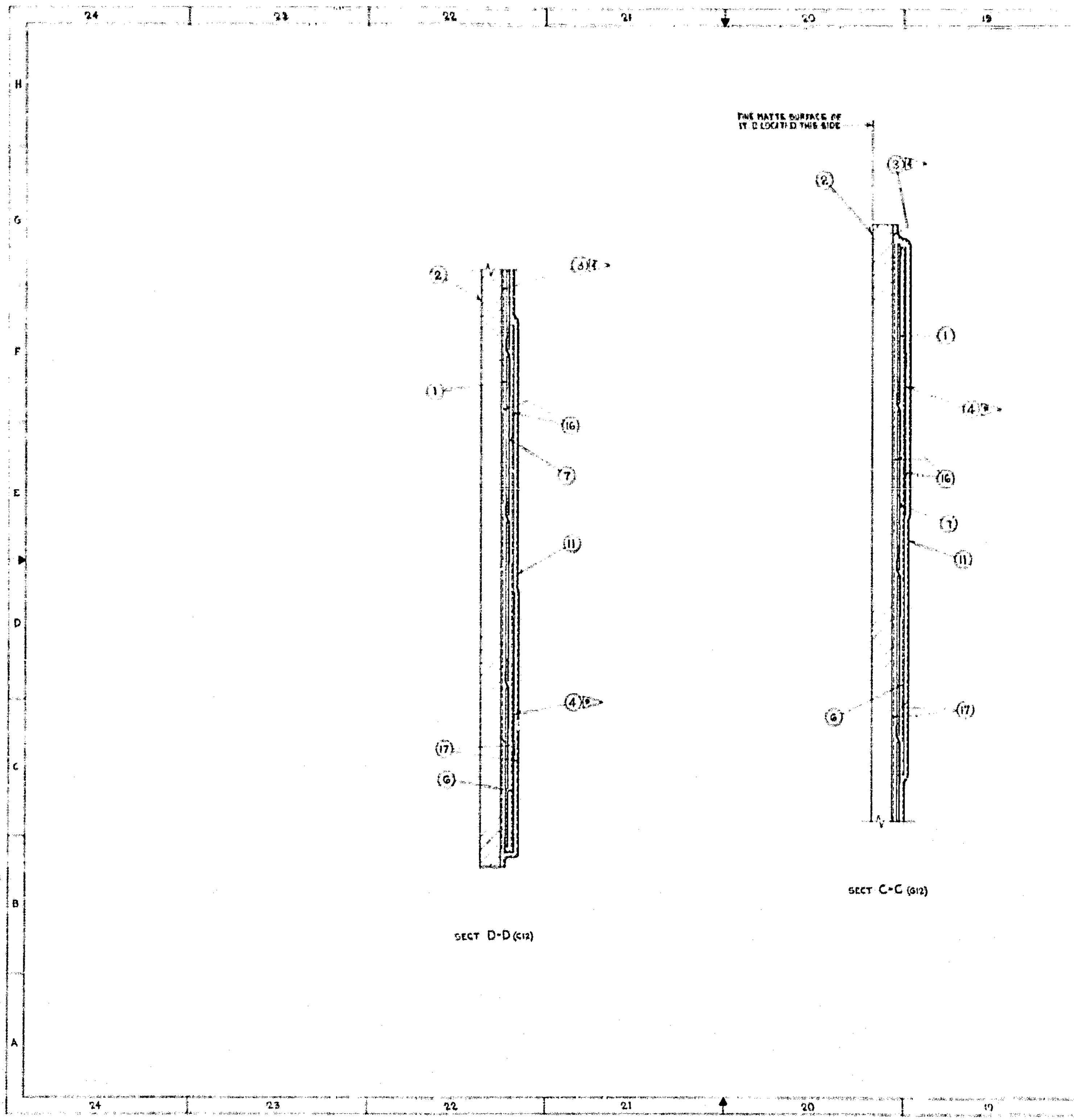
3. TECHNICAL PROGRESS

A. Module Design and Analysis

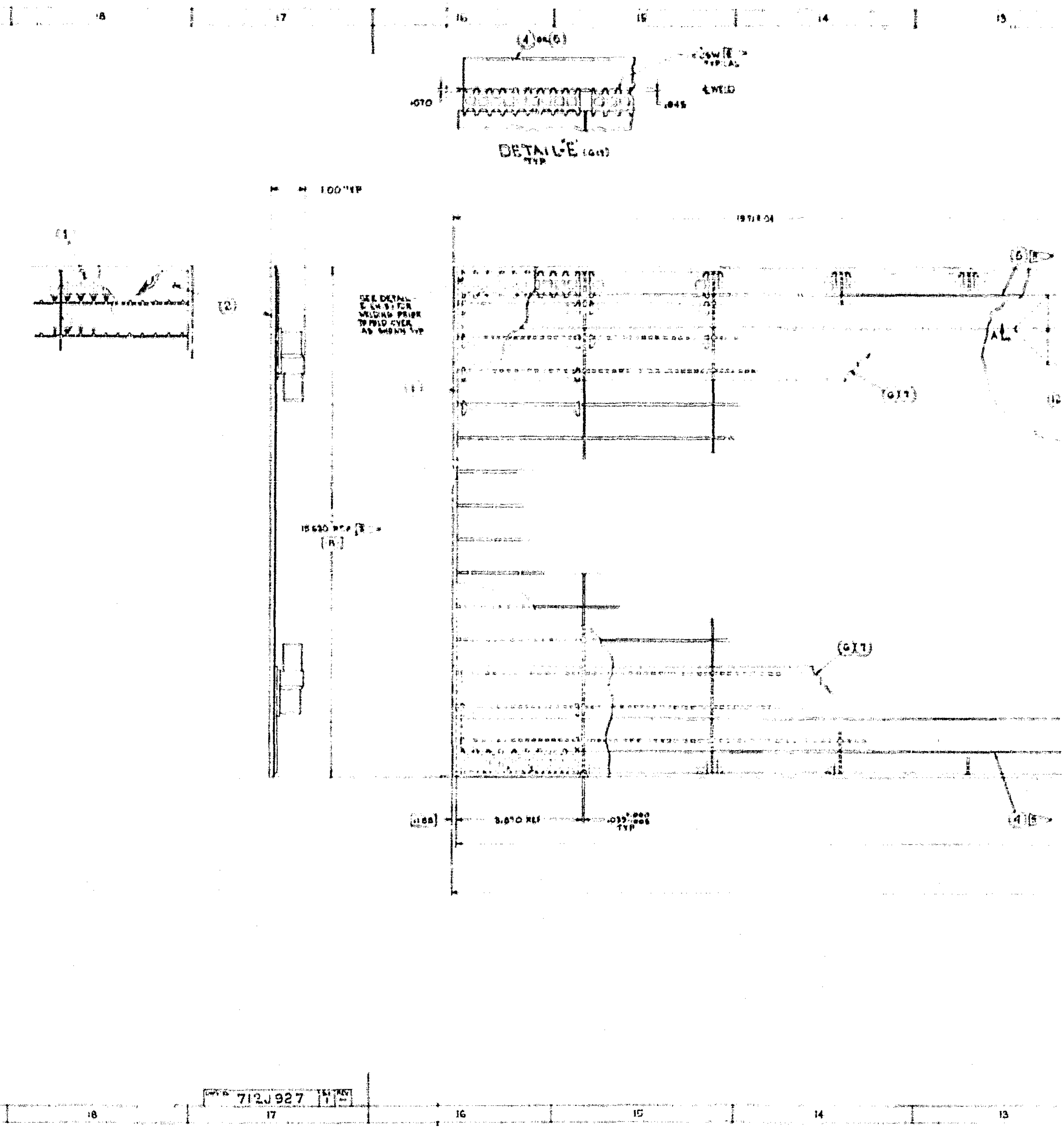
Substantial changes have been made to the Westinghouse MEPSDU module, discussed in the previous quarterly progress report (Westinghouse TME-3090). Most of these changes resulted from suggestions and comments received from JPL personnel at the Preliminary Design Review held at JPL on March 4 and 5, 1981. The revised Westinghouse MEPSDU module design is presented in Figure 1 (Westinghouse Drawing 712J927). This design will be presented in MEPSDU Final Module Design Review meeting to be held at JPL on July 14, 1981.

The most obvious change in the module is that the frame has been eliminated. This change allows placement of photovoltaic cells under a much larger percentage of the superstrate surface. The modules are to be attached to and supported from the array structure, test rack, or roof structure through a structural adhesive system. The adhesive system consists of two components: strips or patches of double-faced polyurethane adhesive tape and a silicone adhesive/sealant. The tape provides immediate low strength attachment and stand-off of the module to the support structure. The adhesive/sealant fills the gaps between the support structure and module and provides a high strength intermediate modulus attachment when cured under ambient conditions. A significant feature of this support system is that application of the adhesive is a field operation rather than a shop operation. No silicones will be present in the shop environment prior to lamination; and the lamination operation is completed several days to several weeks before the module encounters the silicone adhesive.

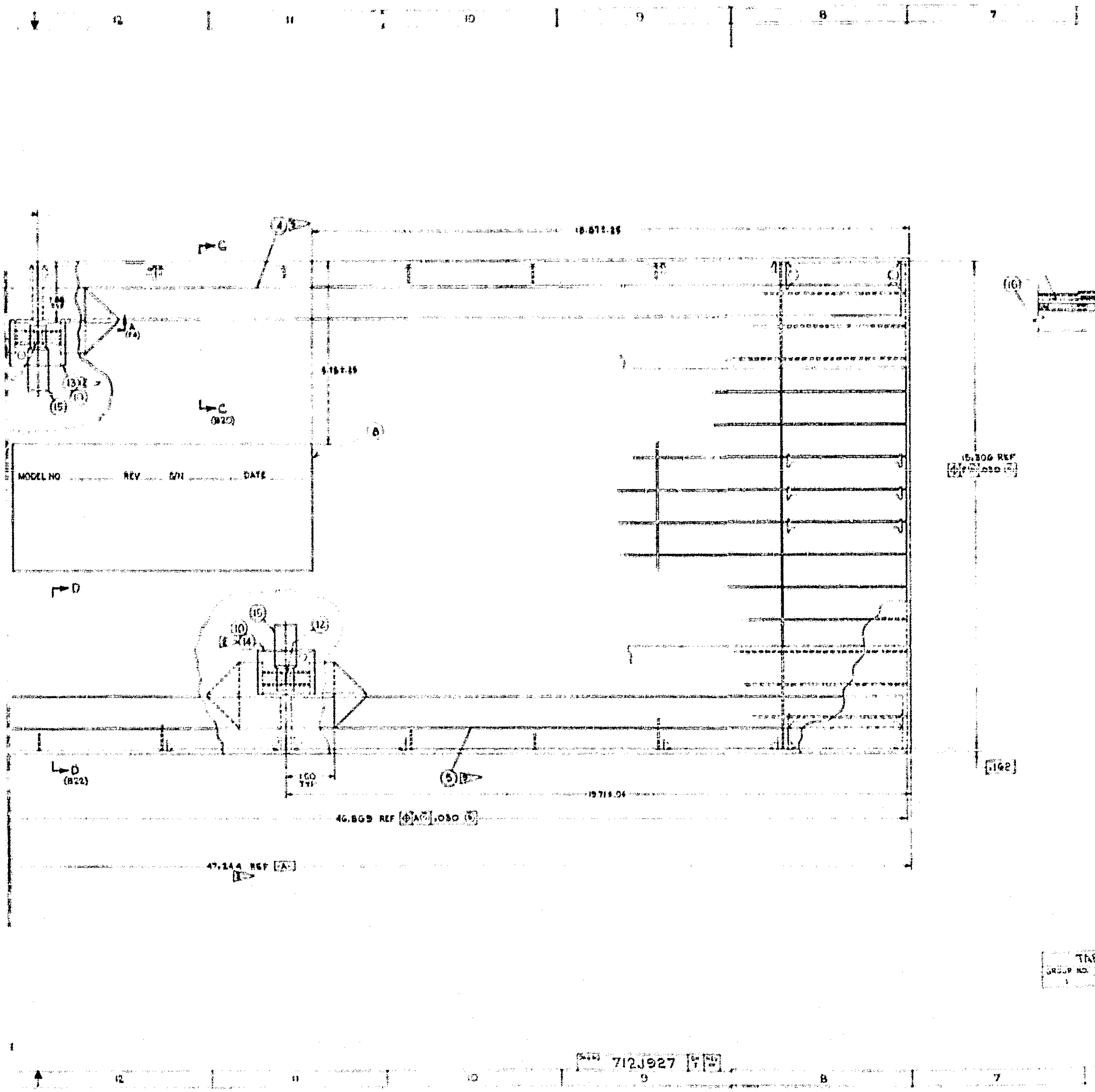
Although this support system has never been used (to our knowledge) on photovoltaic module arrays, it has been used successfully in architectural applications. One installation in the Pittsburgh area is shown in Figure 2. These glass panels are much larger and heavier than the modules (approximately 5 x 7 feet, 1/4 inch thick) and are supported only by the two-component adhesive system. Most of the panels are vertical, but the top course is inclined



FOLDOUT FRAME



FOLDOUT FRAME 2



FOLDOUT FRAME

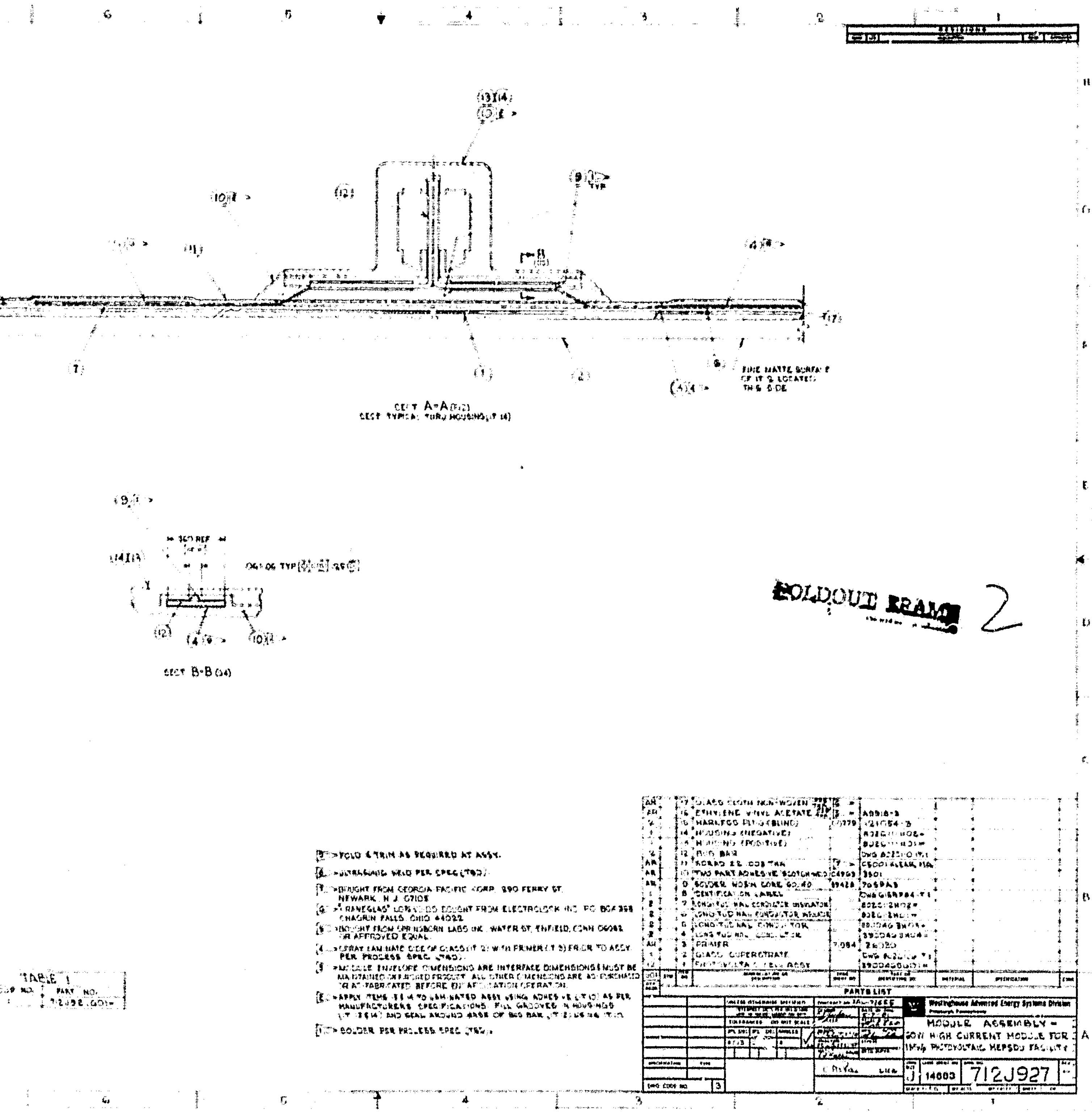


Figure 1. Westinghouse MEPSDU Module Assembly Drawing

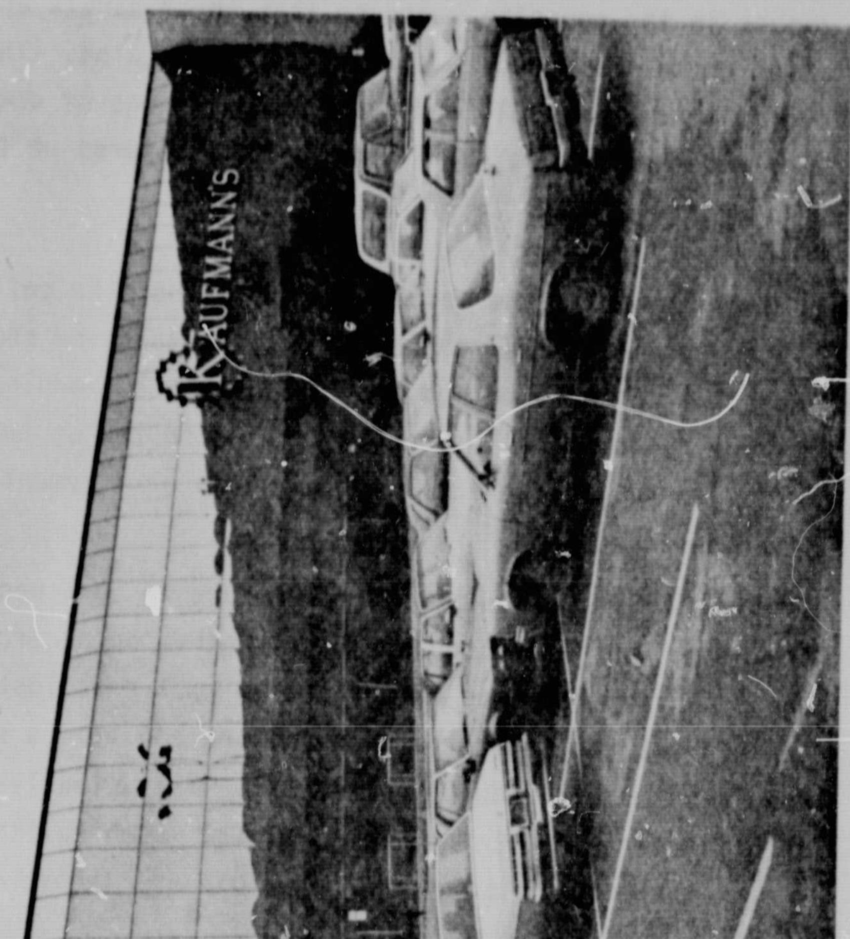


Figure 2. Glass Panelled Wall Utilizing Structural Adhesive Supports

approximately 15° back from the vertical while the bottom course is inclined the same amount in the opposite sense so that these panels are suspended. This installation was designed to survive an 80 mph wind. This particular installation is three years old and has no indications of damage from wind, winter temperatures as low as -20°F, summer temperatures up to 100°F, and severe rain and snow storms.

A second obvious change in the module design is that the cells have been rotated 90° in the plane of the module so that the long and short sides of the cells are parallel to the long and short sides of the module, respectively. This permits the cells to be internally interconnected as twelve parallel strings of fifteen series-connected cells. This arrangement provides two significant advantages:

- If any single cell becomes a nonconducting cell because of cracking, connection separation, or other open circuit failure, the output of only one series out of twelve is lost. With this arrangement and under the cell failure conditions specified, the module output is reduced only 8.33%. This clearly satisfies the specification of JPL Document 5101-138 which calls for the module output to be reduced no more than 10% under these conditions.

- If any single cell becomes a nonconducting cell because of shading, the potential available to force current through it in its high resistance condition is that produced by only 14 cells rather than 44 cells in series as in the previous design. Calculations and preliminary tests indicate that one shaded cell in a series of 15 will survive short circuit operation indefinitely without damage. A similar calculation (without a supporting test) indicates that one shaded cell in a series of 45 may not survive during extended periods of operation under short circuit conditions.

The ability of the prototype MEPSDU solar cell string to survive the short circuit/shaded cell tests specified in JPL Document 5101-138 was determined experimentally using three series connected 5-cell minimodules. The three

modules were connected in a series loop (short circuit) to give a 15-cell array. A thermocouple was taped to the back cover behind the central cell of each of the 5-cell modules. A test system was set up to measure the temperatures and the short circuit current of the modules when exposed to direct sunlight. A standard cell was employed to monitor changing sunlight conditions.

After an initial "soak" period in the sunlight to achieve NOCT, the central cell of the array was shaded. The temperatures and short circuit current of the module and the open circuit voltage of the standard cell were monitored for one hour. The changing sunlight conditions caused the voltage of the standard cell to vary between 11.0 and 56.0 millivolts (60 millivolts = 1 sun). The short circuit current of the array and the cell temperatures varied coincidentally with the recorded changes in the standard cell voltage. The short circuit current of the 15 cell array ranged from 72 to 243 milliamperes, the temperatures of the back cover behind the unshaded cells ranged from 29 to 46°C, and temperature of the back cover behind the shaded cell ranged from 29 to 49°C. The maximum temperature difference between any pair of readings did not exceed 5°C. This test was repeated with the third cell from the end of the array shaded with similar results.

Although the above tests were preliminary and additional tests are planned, these test results strongly suggest that the destructive overheating of a shaded cell during short circuit operation of the module is not a problem with a module design that has strings of 15 series connected cells.

The output voltage of the redesigned module is reduced from 26 V to 8.7 V under standard operating conditions. This, of course, is the results of reducing the number of series-connected cells in each parallel string. The module current is increased by essentially the same factor as the voltage was reduced because the number of parallel strings is increased from 4 to 12.

In any array producing between 10 kW and 500 kW, by definition an intermediate load center (ILC) application, a sufficient number of modules will be used so that almost any desired combination of current and voltage can be obtained. Therefore, this change in the module internal circuitry does not introduce any new problems in the array or the balance-of-plant.

The revised design incorporates cell electrical interconnects with circular punched-out holes, rather than the comb design of the original module. This modification was made at the suggestion of our subcontractor, Kulicke and Soffa Industries, Inc., responsible for the design and fabrication of the MEPSDU automated cell interconnect station. Automated handling of the .0015 inch thick aluminum interconnect tabs is substantially easier with the new configuration.

The necessity for (or the desirability of) a strain relief, such as an S-bend, in the aluminum electrical interconnections between photovoltaic cells has been a concern often expressed during discussions of the Westinghouse module design. This problem has been examined with the conclusion being that a strain relief is not necessary and, because of the cost of producing it, is not desirable. This conclusion is based upon the following logic:

- The simplified geometry of the interconnection is as shown in Figure 3.

- At some temperature below the lamination temperature of the module (150°C), the ethylene vinyl acetate (EVA) matrix will "freeze," i.e., permit no relative movement of the unstressed components. This temperature is conservatively assumed to be 90°C, so that stress calculations can be related directly to the thermal cycling of the module between -40 and +90°C. The actual immobilization temperature is probably nearer 64°C, the softening point of EVA, which would reduce the actual thermal strains.

- The coefficients of thermal expansion of the materials involved have the following values:

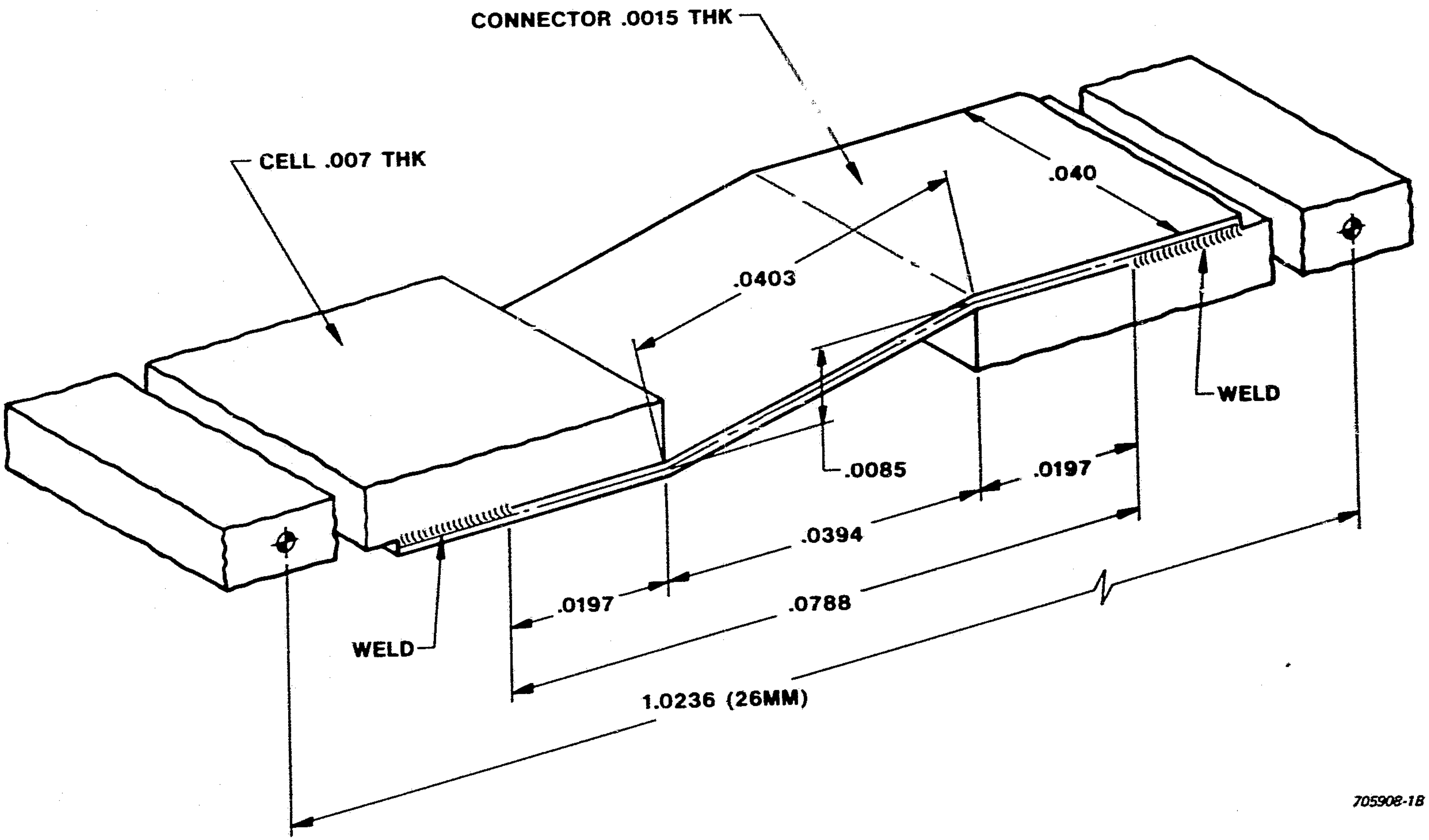


Figure 3. Cell Interconnection Geometry

soda-lime glass	-	$8.46 \times 10^{-6}/°C$
aluminum	-	$23.6 \times 10^{-6}/°C$
silicon	-	2.9 to $7.4 \times 10^{-6}/°C$; the value 7.4×10^{-6} was used in this analysis because it is the less optimistic assumption

- For a cell in a series string with neighbors on both sides, it is assumed that the center of the cell is fixed with respect to the glass superstrate, and that differential thermal expansion is permitted by shear deflection of the low-modulus EVA.

- The relative motion of the edges of the ultrasonic welds in the aluminum interconnection during the 130°C temperature excursion from +90°C to -40°C is calculated to be:

contraction of the glass between centers:	0.00113 inch
contraction of silicon between centers:	0.000910 inch
differential motion:	.000217 inch

- The calculated contraction of the aluminum between the edges of the welds is 0.000245 inch.

- The extension from its free state of the aluminum between welds is calculated to be 0.0000276 inch. This requires a strain of 0.0346%, which in aluminum results in a tensile stress of 3462 psi. The endurance limit of aluminum alloys 1060-H14 and 1100-0 is ±5000 psi. These are the alloys being used in experimental work at Kulicke and Soffa.

- The calculated tensile force in the interconnect tab is 0.208 lbs. The shear stress in the ultrasonic weld, if it is a full area weld, is only 129.8 psi, which is negligible. Tear tests of these welds show approximately full coverage welds, whereas calculations show that as little as 10% coverage would be adequate both electrically and mechanically.

A similar type of analysis was performed to study a second interconnect or bond failure mechanism associated with stresses resulting from differential thermal expansion of the cells and interconnects in the parallel direction. The failure mechanism postulated is successive bond failure during the cold phase of the thermal cycles, beginning at the ends of the cell interconnections and proceeding toward the center of the cell as each bond failure causes its inboard neighbor to become the outboard bond, i.e., the bond acted upon by unbalanced forces. This problem has been examined with the conclusion being that this "domino" failure will not occur and the multiple redundant interconnections will survive thermal cycling. This conclusion is based upon the following logic:

- The ultrasonic bonds between the aluminum interconnections and the silicon cells are made with the spans between bonds at room temperature (21°C); thermal cycling between -40°C and +90°C causes a negative temperature excursion of 61°C and a positive excursion of 69°C.

- The coefficients of thermal expansion of the materials involved have the following values:

  aluminum - 23.6×10^{-6}/°C

  silicon - 2.9 to 7.4×10^{-6}/°C; the value 2.9×10^{-6} was used in this analysis because it is the less optimistic assumption

- During the negative temperature excursion, a thermal strain of $61 \times (23.6-2.9) \times 10^{-6} = 0.001263$ is imposed on the system. It is conservatively assumed that the total strain is imposed on the thin (0.0015") aluminum rather than on the thicker (0.007") and stiffer silicon and that the aluminum provides a direct (straight line) load path between bonds. The calculated equivalent stress for this strain is 16,5000 psi tension, greater than the 13,000 psi yield strength reported for aluminum alloy 1060-H14, and much greater than the 5,000 psi reported for 1100-0; the aluminum would therefore yield. During the positive temperature excursion,

the aluminum, because of its higher coefficient of thermal expansion, would expand more rapidly than the underlying silicon, so that the tensile load would drop to zero. Compressive loading of the aluminum foil will be very slight because the low elastic modulus of the ethylene vinyl acetate clamping the aluminum to the silicon will permit rippling of the aluminum; but upon recooling, the aluminum will again be stressed to its yield strength. An in-line load path in the aluminum between ultrasonic bond pads must therefore be avoided.

- The actual geometry of the aluminum interconnection and the silicon cell is shown in Figure 4.

- Differential strain of the aluminum and silicon can be accommodated by flexure of the aluminum "arch" at its minimum section height. Flexure would occur during both the positive and negative temperature excursions. The greater differential strain occurs during the 69°C positive excursion and is 0.00143. If each half-arch is considered to be a fixed end beam with a tip load sufficient to produce a deflection equivalent to the restraint, the equivalent deflection is .00714 mm or 0.00028 inches. The stress produced by this deflection of the tip of an equivalent cantilever beam at its point of zero deflection (the peak of the arch) is 4106 psi. The corresponding stress during the negative temperature excursion is 3630 psi. Both of these values are less than 5000 psi, the endurance limit (the stress at which an unlimited number of stress reversals can be survived) of aluminum alloys 1060-H14 and 1100-0. Either of these alloys is satisfactory - the selection to be based on mechanical handling of the interconnections during processing. To produce this stress in the interconnections, the shear stress in the end bonds, if these are 0.040" x 0.040", is only 5.06 psi.

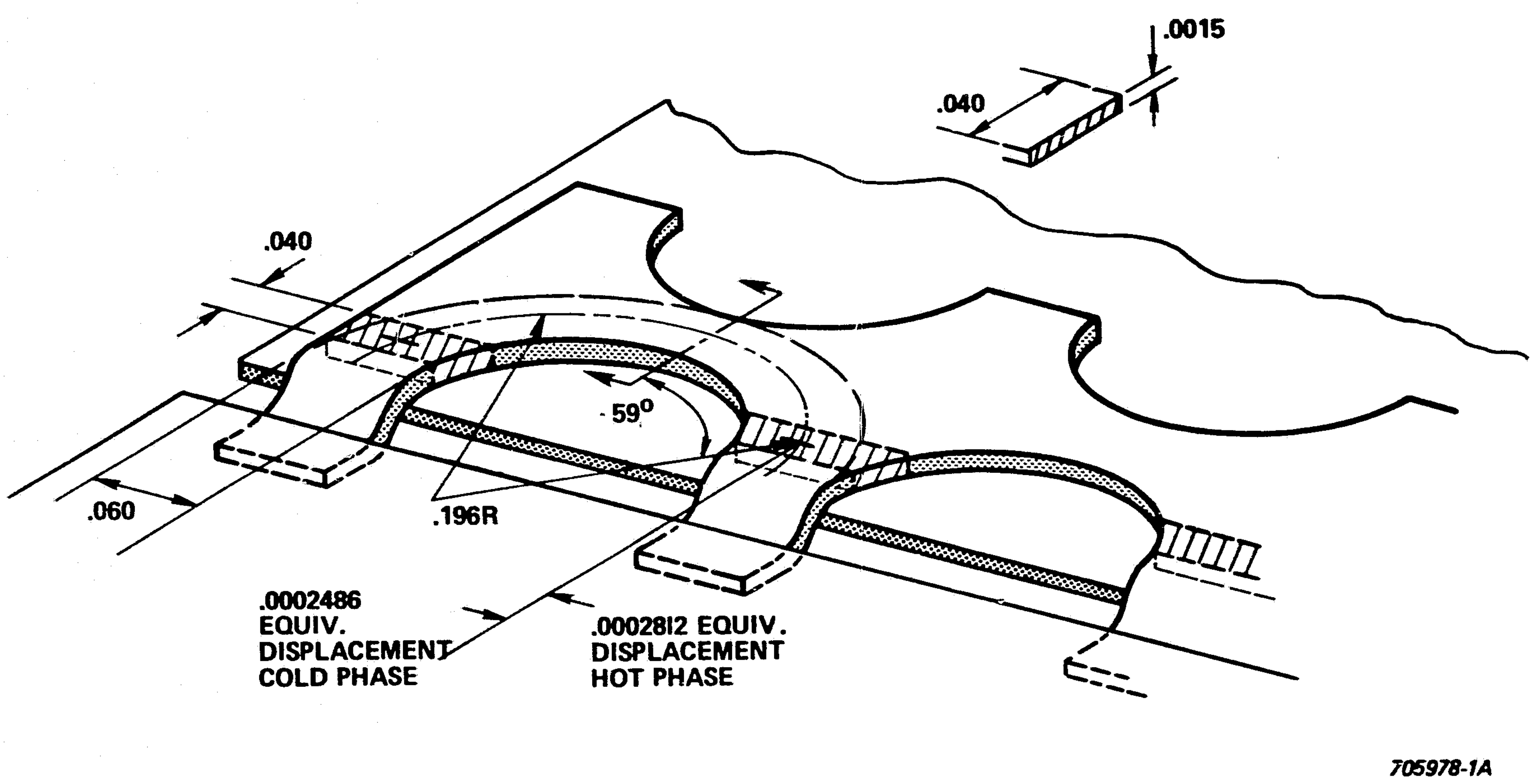


Figure 4. Geometry of Ultrasonic Bonds, Dark Side

Another less significant modification incorporated in the revised design involves the lay-up of the lamination assembly. The lay-up was arranged so that nonporous surfaces (glass or EVA) are always separated by porous layers (Craneglas or the cell strings) to provide adequate passages for pump-down and thus prevent entrapment of bubbles.

B. Process Sequence Design

The preliminary process sequence for the Westinghouse MEPSDU was presented in detail at the Preliminary Design Review at JPL in early March. It was also outlined in a flow chart presented in the previous quarterly report (Westinghouse TME-3090). Because this is a preliminary process sequence, on-going investigations are being made to improve techniques in selected areas and to demonstrate the potential for reducing processing costs. Areas being investigated include: alternate, more cost-effective metallization procedures; ion implantation of front and back junctions to replace the diffusion/cleaning steps; liquid precursor films for diffusion masks and dopants; and dry processing (plasma etching) to reduce wet chemical usage. Each of these areas will be discussed in further detail.

(1) Alternate Metallization Systems

Scoping work on alternate metallization systems to the baseline evaporated Ti/Pd/Cu process was performed during the past quarter. This work has narrowed the number of systems that will be given experimental follow-up to two. These are: (1) electroless nickel deposition on evaporated titanium, and (2) electroless nickel deposition on silicon after proper activation of the surface. In the Westinghouse MEPSDU sequence, particular attention must be given to the effect of aggressive etching or activating solutions upon not only the shallow junctions but also upon the AR and PR coatings which are applied before metallization. This is of greatest concern in the deposition of electroless nickel directly on silicon. Preliminary tests indicate that an effective activating solution for silicon has been identified, but additional testing on cell material is required for confirmation.

Samples of web material have been sent to two vendors of electroless nickel plating solutions. Each of these vendors is currently doing experimental work in his laboratory to develop a satisfactory nickel deposition process for depositing nickel on silicon web. These processes will then be applied to cell material and processed through the Westinghouse pre-pilot line for final evaluation.

An evaporated Ti/Pd/Cu metallization process was presented as part of the preliminary process sequence design. At that time, the possibility of etching the evaporated copper to provide a fresh surface for electroplated copper (with the intent of eliminating the need for plasma ashing equipment) was under consideration. In reviewing the evaporated Ti/Pd/Cu process, it was noted that contamination of the titanium and palladium targets could occur during the vacuum evaporation of copper and that eliminating this possibility by depositing copper in a separate chamber is not cost effective. Therefore, a test was made to change the baseline metallization system to evaporated Ti/Pd, plasma ashing, electroplated copper. This system, comprised of 600 Å Ti, 300 Å Pd, and about 8 microns of copper, had excellent adherence on both the front (grid) and back surfaces and has become the MEPSDU baseline metallization system while the long-range development of alternate metallization systems is underway.

(2) Ion Implantation Studies

The baseline MEPSDU process sequence specifies diffusion for the front and back junctions of the solar cells. The diffusion process, although shown capable of producing high efficiency cells, requires two steps involving high temperature treatment as well as cleaning procedures. To maintain a long carrier diffusion length in the base region of the solar cell, the cells must be slowly cooled from the diffusion temperature. This cooling process requires extra time in the diffusion cycle and sophisticated controls for achieving the proper cooling rate.

As an alternative to the diffusion process, an experiment has been identified and initiated where the junctions are prepared by ion implantation. The purpose of the experiment is to allow a comparison of efficiencies and performance reproducibility characteristics of ion implanted solar cells with the standard diffused junction solar cells.

The ion implantation is being carried out by Spire Corporation of Bedford, Massachusetts. All work performed at Spire will be funded by Westinghouse. MEPSDU contract funds are being utilized for subsequent cell processing work and engineering evaluation work performed at Westinghouse. This task should be completed by July, 1981.

(3) Diffusion Masks and Dopant Studies

The intent of this task is to modify the diffusion process sequence, thereby reducing costs by using less expensive chemicals, less involved procedures, simplified equipment and controls, and by defining a process more amenable to total automation.

An initial experiment was conducted in May to determine if the Westinghouse antireflective coating (a TiO_2-SiO_2 solution in alcohol) could be used as a diffusion mask replacing CVD SiO_2. It has been observed that, although the formation of an SiO_2 film from silane oxidation produces an effective diffusion mask on one side of the web, there is always some spotty deposition on the reverse side; and a quick acid dip is required to provide a clean surface for diffusion. A film from a liquid precursor can be applied to one surface and, thus, eliminate the acid clean up.

There were two groups of web used in the experiment with the antireflective coating: Group No. 1 used the standard SiO_2 (Silox) masking before boron and phosphorous diffusion and Group No. 2 had our antireflective coating solution painted on one side of the web before diffusion.

It was difficult to etch the antireflective coating from the web after diffusion, particularly after phosphorous diffusion. In order to process this group into cells, it was necessary to acid scrub to remove the coating; and this procedure gave cells that were slightly discolored.

Test data from the cells indicated that the antireflective coating does act as a diffusion mask in that the measured cell parameters from the two groups were the same. However, the etching behavior of the coating precludes its use in a production facility. The experiment will be repeated using a metal-organic precursor containing only SiO_2 to determine if the film that is formed is easier to remove by etching.

(4) Dry Processing

A task has been undertaken to investigate the use of dry plasma processing to replace many of the wet chemistry steps identified in the baseline process sequence. These include pre-diffusion cleaning, oxide removal, and surface clean up prior to metallization and plating.

The baseline MEPSDU pre-diffusion cleaning sequence projects an HF dip (actually a scrubbing station is required) followed by a CF_4/O_2 plasma etch. The active species formed by an rf glow discharge react with impurities on the silicon surface, and they are removed as volatile products that are pumped from the system.

Recent scoping experiments using raw web indicate that an agitated HF dip is inadequate in removing both loose and adherent oxice, but that both types of oxide are removed by lightly rubbing the surface with an HF saturated swab prior to plasma etching. Samples that had the best plasma etched appearance were processed in standard 96% CF_4:4% O_2 etching gas for 2 min. at 300 watts or 10 min. at 100 watts. Those processed for longer times or at higher powers exhibited roughening of the surface.

A test was made in which three sets of samples were pre-diffusion cleaned as follows:

Group I - Web wiped with cotton swab and plasma etched.
Group II - Web wiped with HF/H_2O and plasma etched.
Group III - Web given standard pre-diffusion cleaning.

These groups, containing a total of 32 cells, were then processed together through the pre-pilot line facility.

Web from Group I (dry wiped with a cotton swab to remove loose oxide) had, in many cases, a post-plating copper haze and yielded cells of poorer quality than did web swabbed with the acid solution. In general, cells produced from web given an acid swab and a plasma etch were equal to those produced from web given the standard pre-diffusion cleaning process.

(5) Laminate Environmental Tests

Twelve small modules were assembled for environmental testing during the past quarter. These modules were made to evaluate several different layups, substitutes for Korad-KLEAR as the back surface weather seal, and Tedlar tape as an edge seal. Cells with efficiency levels unacceptably low for incorporation into modules were selected for use in these tests. Cut window glass was used on all the test modules rather than tempered float glass which will be used on the MEPSDU modules. Three of these modules were used in the shading tests discussed in an earlier section of this report. The layup of each of these modules is shown in Table 1. The following comments are made in regard to the appearance of the as-laminated modules. The sun side of module G-2 was clearer than the modules that had a layer of Craneglas between EVA and the window glass. The back surfaces of modules with Korad back covers (G-1, G-2, G-3, G-10, G-11, and G-12) were wrinkled transverse to the long direction of the cells. The back surfaces of modules made with 2 mil thick Tedlar back covers (G-4, G-6, G-7, and G-8) were fairly smooth. The 4 mil thick Tedlar back cover of module G-5 was extremely smooth. The use of EVA primed Tedlar (G-7 and G-8) simplified the layup. The Acrylar back cover of module G-9 was extremely wrinkled with a random orientation. The use of Elvax* (non-blocking EVA) in module G-11 produced no noticeable difference in lamination or module performance. Because it is non-blocking, it is much easier to handle. The elimination of Craneglas behind the cell string in modules G-10, G-11, and G-12 also had no adverse effect on either appearance or performance. The white back covers made it possible to observe shrinkage/wrinkling effects that suggest that all back cover materials should be cut slightly oversize prior to lamination. The shrinkage/wrinkling effects were not easily detected with clear back covers because of the transparency of all of the films used in the layups. The cut window glass did not have an edge of the quality of manufactured tempered float glass; therefore, the Tedlar tape edge seal did not "corner" well on all sides of modules G-2, G-4, and G-9.

A typical test module is shown in Figure 5.

*DuPont Trade Name

TABLE 1

LAYUP OF SMALL MODULES USED FOR ENVIRONMENTAL TESTING

G-1	G-2	G-3	G-4	G-5	G-6
(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)
Window Glass	Window Glass	Window Glass	Window Glass	Window Glass	Window Glass
Craneglas	EVA	Craneglas	Craneglas	Craneglas	Craneglas
EVA	5 Cell String	EVA	EVA	EVA	EVA
5 Cell String	Craneglas	5 Cell Stirng	5 Cell String	5 Cell String	5 Cell String
Craneglas	EVA	Craneglas	Craneglas	Craneglas	Craneglas
EVA	Craneglas	EVA	EVA	EVA	EVA
Craneglas	Korad-KLEAR	Craneglas	Craneglas	Craneglas	Craneglas
Korad-KLEAR	Tedlar Edge Tape	White Korad	Clear Tedlar (2 mil)	Clear Tedlar (4 mil)	White Tedlar (2 mil)
			Tedlar Edge Tape		

G-7	G-8	G-9	G-10	G-11	G-12
(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.6 x 9.4 cm cells)	(1.2 x 10 cm cells)	(1.2 x 10 cm cells)	(1.2 x 10 cm cells)
Window Glass	Window Glass	Window Glass	Window Glass	Window Glass	Window Glass
Craneglas	Craneglas	Craneglas	Craneglas	Craneglas	Craneglas
EVA	EVA	EVA	EVA	Elvax	EVA
5 Cell String	5 Cell String	5 Cell String	5 Cell String	5 Cell String	7 Cell String*
Craneglas	Craneglas	Craneglas	EVA	Elvax	EVA
{EVA Primed Clear Tedlar (2 mil)}	{EVA Primed White Tedlar (2 mil)}	EVA	Craneglas	Craneglas	Craneglas
		Craneglas	White Korad	White Korad	Korad-KLEAR
		Acrylar X-22417			
		Tedlar Edge Tape			

*K&S bonded

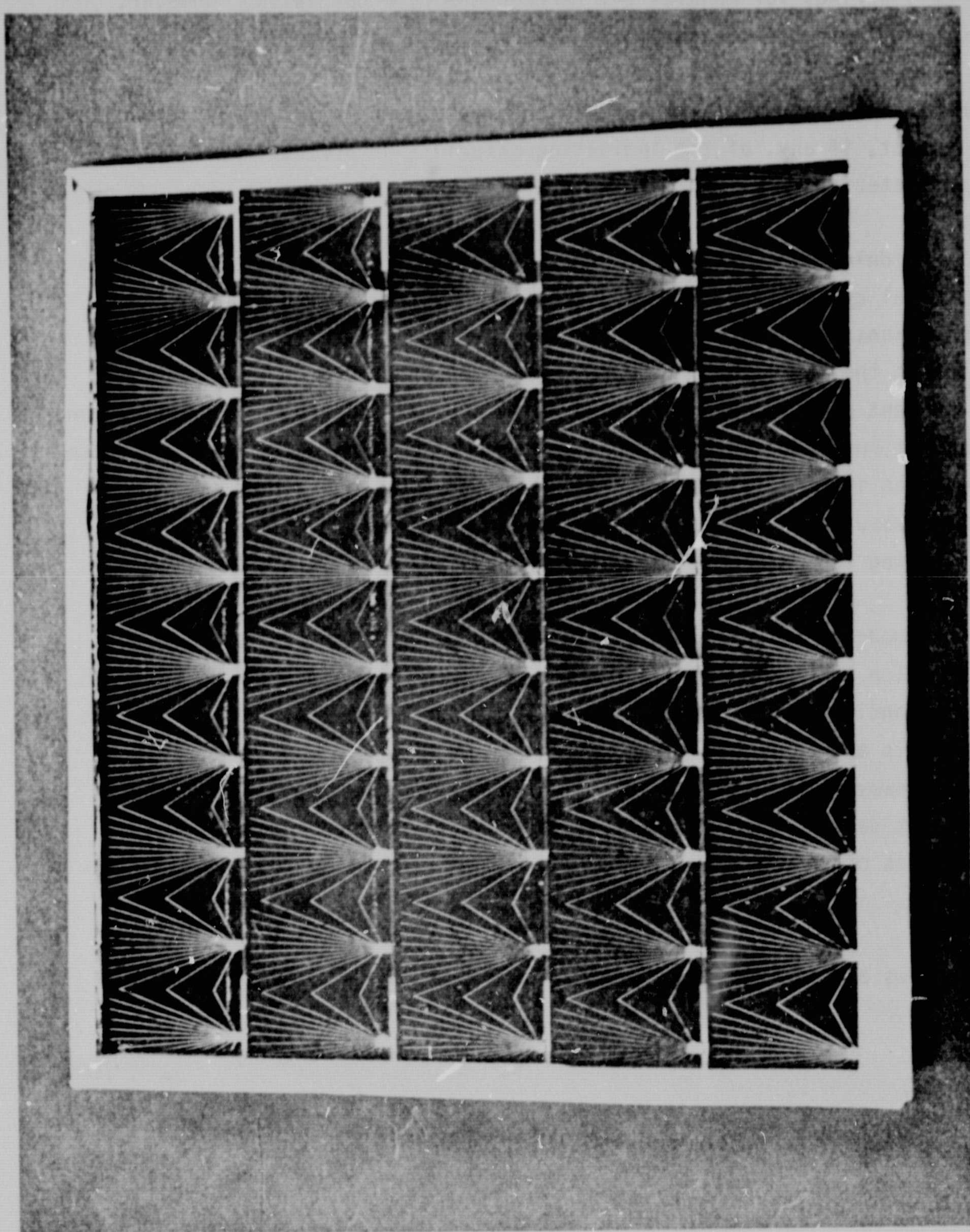


Figure 5. Environmental Test Module G-2 (10 cm x 9 cm)

Because of a malfunction of the test equipment, pre-lamination measurements made on cell strings for modules G-1 through G-9 were not valid. However, pre- and post-lamination measurements were obtained on the cell strings in modules G-10, G-11, and G-12, and these data are shown in Table 2. The differences seen in the data are within the measurement error of our equipment; and the effect, if any, of the laminating materials or process upon cell or module characteristics is minimal.

All twelve modules were placed in an environmental test chamber and subjected to the thermal cycles specified in JPL 5101-138, Figure 5.1. (Due to equipment limitations, the minimum temperature achievable in these tests is -35°C as opposed to the specified level of -40°C). Open circuit voltage and short circuit current measurements were made on each of the modules after lamination, after completion of 25 cycles, and again after completion of 50 cycles. These data are given in Table 3. As before, the differences seen in the data are within the measurement error of our equipment. The effect, if any, of the thermal cycling test upon cell or module characteristics is not measurable.

Each of the modules was examined after the thermal cycling test. There was some separation of the lamination from the glass on modules G-1, G-3, and G-5 and some debonding of the edge tape from the glass on module G-2. These were random effects and could not be correlated to materials or processes. They are noted, however, because it is planned to subject these modules to the humidity test defined in JPL 5101-138, Figure 5.2; and the separation may permit ingress of moisture by a route other than permeation through the lamination films.

Figure 6 shows all twelve modules after completion of the thermal cycling.

TABLE 2

PRE- AND POST-LAMINATION MEASUREMENTS OF CELL STRING CHARACTERISTICS

Module	Pre-Lamination Cell String Characteristics				Laminated Module Characteristics			
No.	Voc (V)	Isc (A)	FF	η (%)	Voc (V)	Isc (A)	FF	η (%)
G-10	2.60	.298	.77	9.92	2.66	.283	.77	9.69
G-11	2.52	.309	.74	9.60	2.69	.295	.75	9.92
G-12	3.58	.297	.73	9.24	3.75	.273	.75	9.04

NOTE: All cells used in the assembly of these test articles were produced during early checkout operations on the Westinghouse pre-pilot facility. These efficiency levels are not representative of the pilot line or the MEPSDU process sequence.

TABLE 3

MEASUREMENTS MADE ON THERMALLY CYCLED TEST MODULES

Module No.	Open Circuit Voltage			Short Circuit Current		
	As Laminated	After 25 Cycles	After 50 Cycles	As Laminated	After 25 Cycles	After 50 Cycles
G-1	2.58	2.61	2.52	.318	.340	.337
G-2	2.58	2.62	2.60	.278	.295	.285
G-3	2.57	2.63	2.61	.326	.351	.345
G-4	2.46	2.61	2.60	.330	.339	.330
G-5	2.48	2.53	2.52	.246	.266	.256
G-6	2.52	2.58	2.57	.262	.281	.272
G-7	2.51	2.55	2.57	.265	.280	.271
G-8	2.54	2.59	2.60	.267	.288	.283
G-9	2.58	2.63	2.64	.330	.346	.335
G-10	2.66	2.68	2.69	.283	.303	.294
G-11	2.69	2.71	2.71	.295	.309	.299
G-12	3.75	3.77	3.75	.273	.283	.272

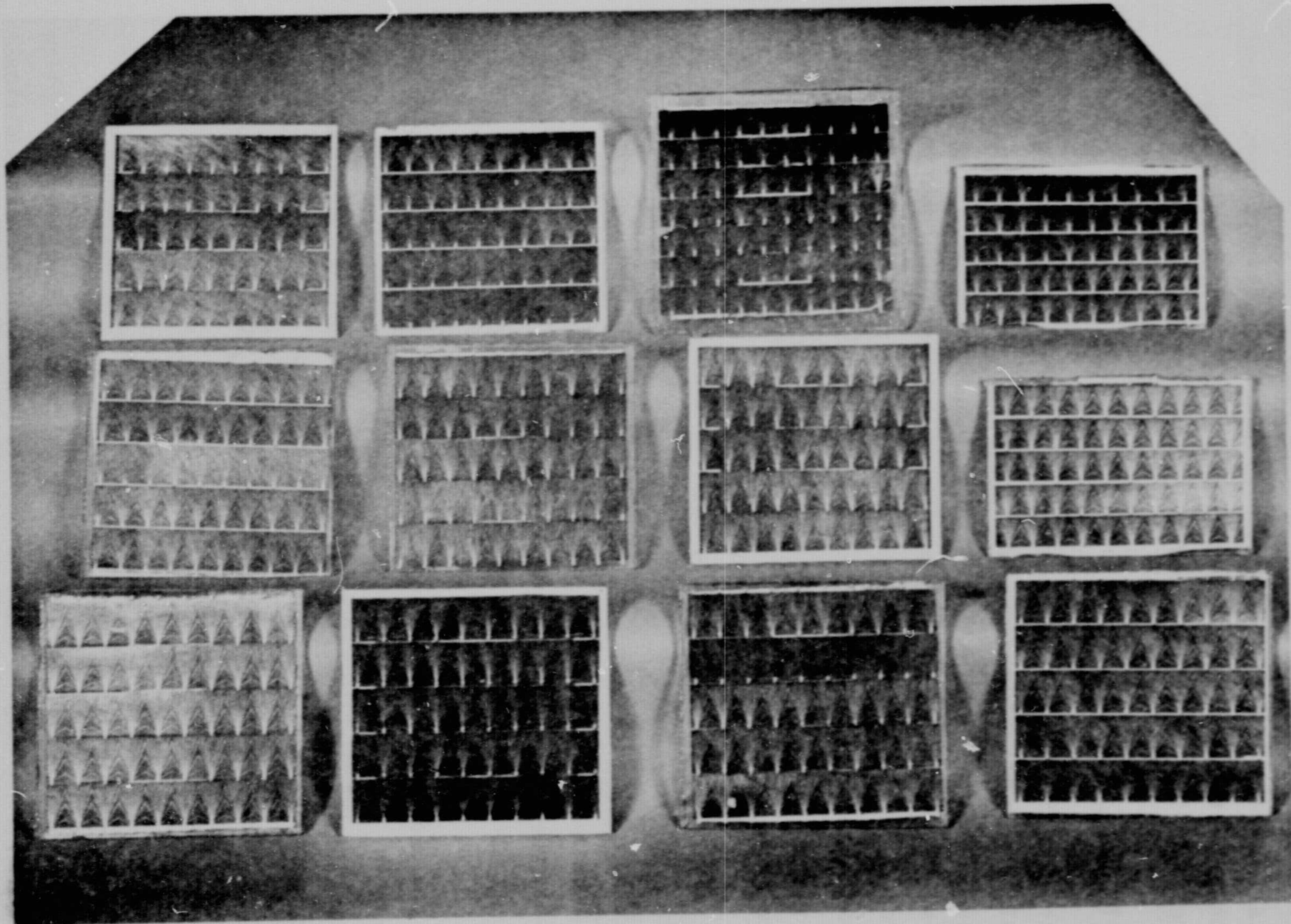


Figure 6. Test Modules G-1 through G-12 after Thermal Cycle Testing

C. MEPSDU Design

This task is associated with the design or specification of equipment required to perform all operations of the Westinghouse MEPSDU process sequence. Final selection of most items has been deferred due to FY'81 budget reductions. However, the following effort was completed during the past quarter:

(1) Diffusion Furnace

An equipment specification (E-Spec) was prepared for the diffusion furnace system required to perform front and back junction formations, as included in the baseline process sequence. Firm fixed price quotations were received from four vendors. A final selection has been postponed until late 1981, and the specification could be substantially affected by results of the ion implantation junction formation study described in an earlier section of this report. Due to the planned delay, it will be necessary to obtain new quotations on the equipment regardless of specification development.

(2) AR and PR Application Stations

Several vendors, each with different application techniques, have expressed interest in the antireflective (AR) and photoresist (PR) application stations. Two of these vendors requested and were supplied with sheet material for tests of their application techniques during the past quarter.

One vendor applied the AR coating in a spray coating system and returned the coated pieces for our evaluation. The coating was not uniform (spotty). It was apparent that the spray droplets did not wet the silicon surface well enough to spread and blend together before the solvent evaporated. It bore no resemblance to the coating applied by our controlled rate of withdrawal of strip from a tank containing the AR coating solution.

The second vendor applied the AR coating in a meniscus coating system and returned the coated pieces for our evaluation. The coating was uniform but thick since the vendor could not measure the thickness. However, the application technique is promising, and the vendor has been supplied with additional sheet material for further development of his technique.

Both the spray and meniscus coating techniques are of interest because they apply coating to only one side of the web and can be easily adapted to form part of an in-line processing system in the MEPSDU coat, bake, expose, develop, and etch sequence.

(3) Photoresist Exposure and Development Station

Several vendors have proposed equipment for the PR exposure and development station, but decisions on this equipment will be deferred until the technique used to apply the PR coating has been selected.

(4) Metallization Box Coater

An E-Spec was prepared for the metallization box coater required to perform base metal application (Ti/Pd) as included in the baseline process sequence. Firm fixed price quotations have been received from five vendors. A final selection has been postponed until late 1981, and the specification could be substantially affected by results of the alternate metallization systems currently under investigation and described in an earlier section of this report. As with the diffusion furnace, the quotes will expire prior to final selection.

(5) Metal Rejection/Plating Station

The selection of a technique for rejection of excess metal will not be made until the results of some of the process sequence studies, described in an earlier section of this report, are completed. These studies will determine if there is a need for, or an advantage to, the use of a plasma stripping unit to prepare metallized surfaces for electroplating.

A preliminary equipment specification was initiated for the electroplating system, but its completion has been deferred until work on the overall metallization process sequence selection has been completed.

(6) Cell Separation Station

In the MEPSDU process sequence, the separation of the discrete solar cells from the dendrite-web matrix is accomplished by scribing the cell outline on the back of the web strip and fracturing out the individual cells. This scribing is accomplished using a Nd:YAG laser and penetrating the back surface of the web strip about one third its thickness.

An equipment specification for a laser scribe suitable for the MEPSDU throughput has been prepared, and copies were included in the preliminary design review data package.

The laser scribe system described in the equipment specification consists of the following elements:

1. Nd:YAG laser powered by krypton arc lamps.
2. Positioning fixture such that the web can be aligned to assure proper scribing directions and distances. This alignment is specified to be automatic - the operator constrained only to placing the web strip in a defined area.
3. A control unit which can be programmed to drive the fixture (or move the laser beam) through the required scribing path.

Item #2 is of prime importance in meeting the MEPSDU throughput requirement.

This equipment specification was sent to eleven manufacturers of laser equipment, and three firm quotes have been received.

The equipment cost, delivery time, and degree of responsiveness of the three proposals are now being evaluated with special emphasis on the proposed alignment technique.

It is planned to initiate a purchase order in June.

D. Automated Cell Interconnect Station

The Westinghouse MEPSDU has been designed using automated processing stations to the maximum extent feasible for a line of its size. Material transfers, for the most part, are manual. Automation of these transfers involves straightforward insertion, retrieval, or translations of cells or cell holding fixtures. The Westinghouse dendritic web cells are easily manipulated during operations performed prior to dendrite removal because the dendrities provide additional strength and ideal gripping surfaces.

The most difficult cell handling operations are those performed after the cell separation operation in which the dendrites are removed. The Westinghouse MEPSDU will demonstrate suitability for automated handling equipment for the dendritic web cells by totally automating the cell interconnect operation. Equipment and processes for the material transfer portion of this station are representative of those required in other stations.

Westinghouse has selected Kulicke and Soffa Industries, Inc., as its subcontractor for the design and development of MEPSDU equipment dealing with the automation of interconnection and assembly of its dendritic web silicon solar cells into modules. This subcontract deals with design, development, testing, and operation of equipment, and preparation of instruction manuals for the automated interconnect station.

The solar cell electrical interconnect configuration to be utilized by the interconnect station will be thin (.001 to .002") aluminum tabs connecting metallized pads located on the front surfaces of each cell with the metallized rear surface of the adjacent cell. The technology to be used to join aluminum tabs to metallized cell surfaces will be ultrasonic bonding. However, to minimize technical risk, the equipment developed for this application will be convertible to solder reflow bond technology.

(1) Electrical Interconnect Bonding Technology Selection

Engineering work on this task continued throughout the quarter. The primary objective of this work effort is to select one of three candidate bonding techniques: seam bonding, rolling spot bonding, or reflow soldering.

Rotary seam bonding is the primary ultrasonic technique being considered for the automated cell interconnect stations (see Figure 7). Ultrasonic bonding represents a clean, fluxless technique which can enhance the cost effectiveness of the Westinghouse cell and metallization configuration.

Seam bonding experiments are being conducted using equipment procured by Westinghouse and shipped to K&S for this purpose. In April, an "improved" seam bonder built by Sonobond, Inc., was put into operation. This equipment is shown in Figure 8. Improvements involved the use of a ceramic ultrasonic transducer and a power supply incorporating a phased locked loop circuit to maintain the required current-voltage relationship throughout the bonding process. A substantial improvement in yield, bonding strength (as determined by pull tests), and bonding speeds have been observed with the new equipment. Successful bonds have been made with speeds up to .75 in/sec to date whereas 2 in/sec speeds are required to achieve MEPSDU throughput objectives.

A mechanical lifting device has been successfully incorporated to prevent contact between the bond head and the cell except at the interconnect pads where the bonds are made. This will prevent potential cell damage resulting from rolling contact of the bonding wheel across nonmetallized cell surfaces.

Experimentation has also begun using an Orthodyne ultrasonic bonding unit which has been configured to produce a "rolling spot bond.' A greater bonding force (up to 550 gms) can be applied with the spot bonding equipment because of the improved force distribution inherent with this configuration. With the higher bonding forces, much harder aluminum interconnects can be readily bonded. The harder aluminum will be easier to handle in the automated cell interconnect station.

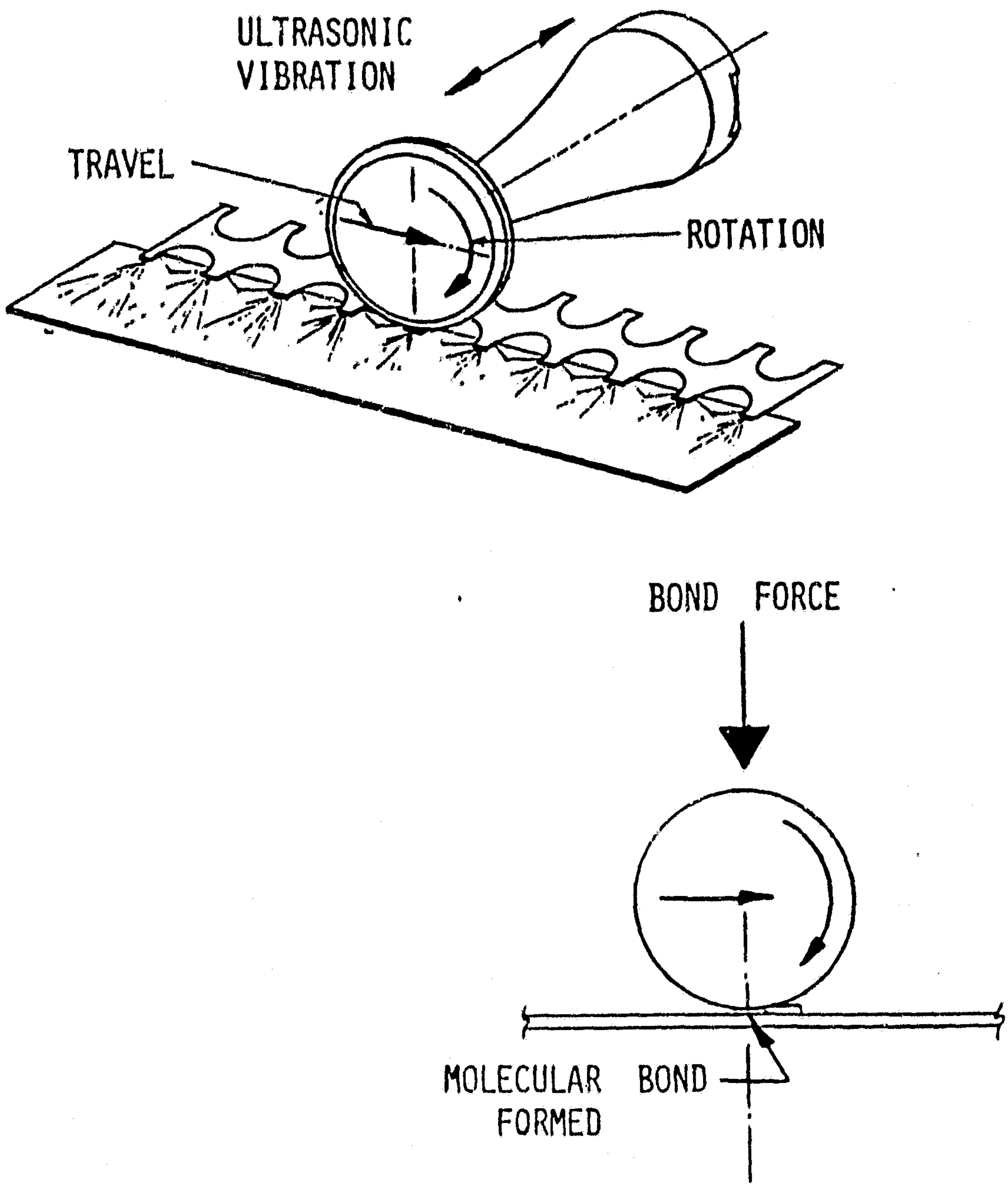


Figure 7. Rotary Ultrasonic Seam Bonding

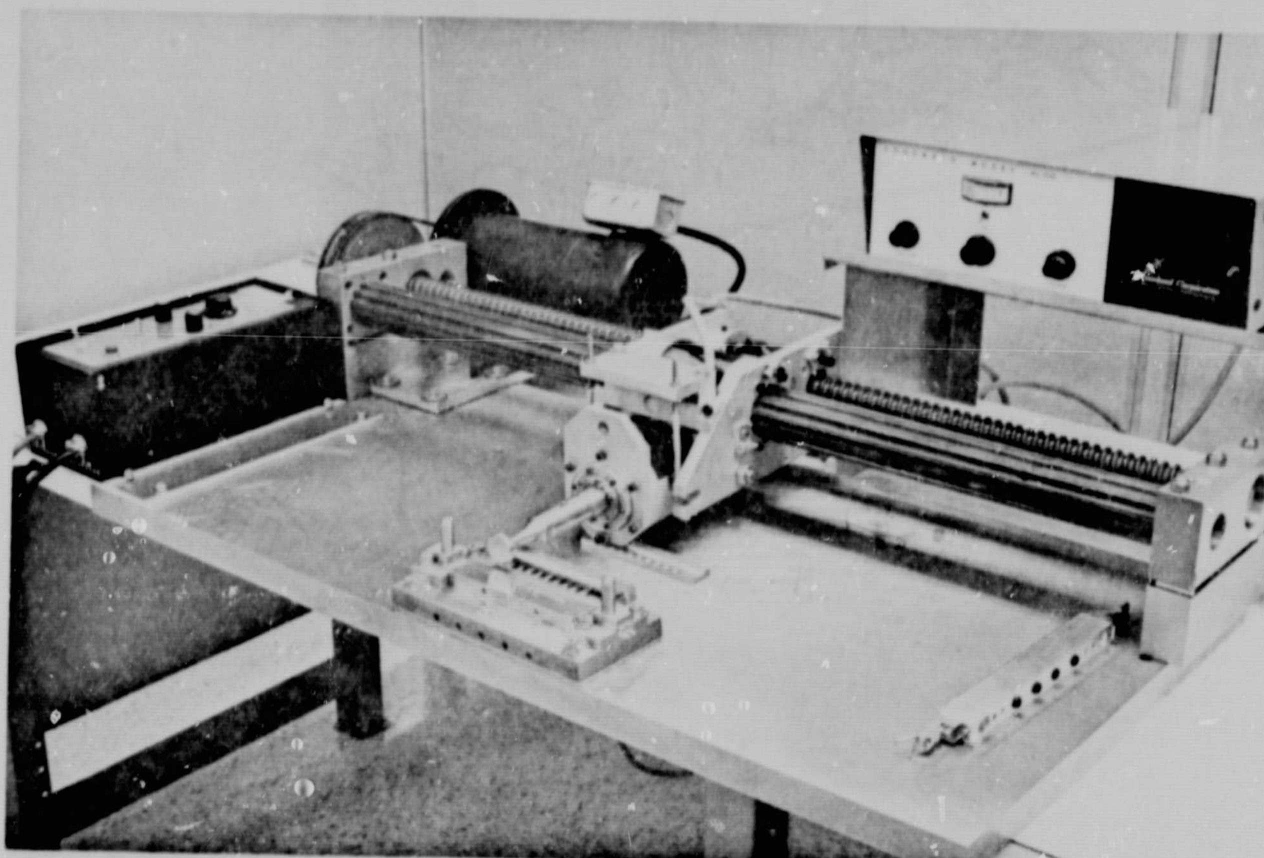


Figure 8. Sonobond Rotary Seam Welder

A major advantage of the rolling spot bonder is that the transducer head and bonding tool are much less massive than the Sonobond equipment and thus can be more easily accelerated and decelerated to allow rapid motion from one cell pad to the next. This rapid motion is necessary to achieve the .5 second time limit required to complete all nine front surface bonds. The rolling spot bonder also affords the opportunity of using multiple bond heads to speed up the process.

Pull-test forces achieved with the rolling spot bonding experiment have averaged about 150 grams. This is about 50% higher than has been achieved with the Sonobond seam bonder.

Additional work was performed to study feasibility of bonding copper interconnects to the copper plated pads on the Westinghouse cells. To date, however, no success has been achieved in ultrasonic bonding of copper interconnects.

(2) Machine Concepts

The basic machine concept for the automated cell interconnect station remains as described in the previous quarterly progress report (Westinghouse TME-3090). Preliminary layouts of the cassette unload station were completed during this quarter. The unit will be capable of holding up to 4 cassettes at a time with each cassette typically holding 25 cells.

Layouts of the interconnect stamp and feed system are proceeding. These layouts will be used to evaluate the forming of interconnects at the machine versus feeding pre-stamped interconnects.

(3) Control System

Effort has been initiated on the identification of a machine control system. The control system intended to be utilized for the interconnect station is a programmable controller that is compatible with, and can be enhanced by, microprocessor and servo circuitry. A programmable controller will provide the flexibility desired in such equipment along with relative simplicity in programming, operation, and maintenance.

Various commercially available programmable controllers have been evaluated with these factors in mind:

- Memory - Type and back-up
- Scan time (per 1K of memory)
- Types of input/output (I/O) interface available
- Programming features
- Service availability
- Manufacturer experience
- Price - based on:
  - Basic processor
  - Minimum memory
  - 150 I/O capability

Based on these factors, the programmable controller tentatively chosen to be used in the Allen-Bradley PCL-2/20.

E. Economic Analysis

Significant progress was made during the past quarter in analyzing costs for fabricating photovoltaic modules from dendritic web using the Westinghouse MEPSDU process sequence. This analysis is being performed using the SAMICS computer code and assuming a 1 MW per year production rate (the MEPSDU capacity and referred to as the "M-Process"). To assure that this process sequence is an efficient step toward high volume, low cost production, a similar analysis is also underway assuming a 25 MW/yr production rate (referred to as the "P-Process").

The following is a list of the assumptions used in preparing the input data for the SAMICS formats:

a. 3 shift, 7 days per week, 345 days/yr operation (4.97×10^5 operating minutes/yr).

b. In the M-Process, throughput rate is 200 cm^2/min of usable web (99.4×10^2 m^2/yr). With a nominal 12% module efficiency, the line capacity will exceed one MW/yr. The actual electric output of the line is based on the assumed wattage of the module and the yield factors assumed.

c. In the P-Process, a throughput rate of 5000 cm^2/min is assumed (2.485×10^5 m^2/yr). With a nominal 12% module efficiency, the production capacity of the line will exceed 25 MW/yr.

d. The strips of dendritic web silicon input into the line are 42 cm long by 2.7 cm wide. From each strip, four 2.5 cm x 10.0 cm cells will be fabricated.

e. The modules fabricated are a nominal 16" x 48" (40 cm x 120 cm) and produce 60 watts at 28°C and 100 mW/cm^2 insolation.

f. Yields for the process sequence are taken into account in two places in the process sequence. First, after cell test, and second, after module test. For ease in computation, these are listed as separate (no cost) steps in the process sequence.

g. All machines are listed as being operational 100% of the time. The various pieces of equipment have been sized such that the required throughput can be obtained assuming industry experience. Any major maintenance will be carried out during the 20 days/year downtime.

Format A's for both the M-Process and the P-Process were prepared in May. Successful runs have been made using our AESD computer terminal. Results are currently being reviewed and will be presented, along with a detailed description of the input data, in a separate topical report. This report will be published in June.

F. Documentation

(1) Quality Assurance Plan

The Preliminary Quality Assurance Plan was submitted to JPL at the Preliminary Deisgn Review (PDR) held at JPL during this quarter. Presented along with the plan was an outline of the content of a quality inspection proceudre that will be developed for final workmanship inspection of MEPSDU modules. Further action in this area has been deferred to October, 1981.

A general safety and health plan has been partially drafted for the MEPSDU facility. Completion of this plan is being delayed to take advantage of an overall Westinghouse division safety manual which is being issued chapter by chapter at AESD and is currently about half complete.

Product Assurance personnel continue to participate in the investigation and evaluation of potential suppliers for MEPSDU. In conjunction with this effort, review and input has been provided by Product Assurance to equipment specifications to be used in procurement of all MEPSDU facilities.

(2) Programmatic Documentation Submittal Status

All programmatic documentation specified in the Westinghouse MEPSDU contract has been submitted in accordance with schedular requirements. A list of the programmatic documentation and submittal dates are compiled in Table 4.

TABLE 4

PROGRAMMATIC DOCUMENTATION SUBMITTAL STATUS

ITEM	SUBMITTAL DATE(S)
1. COST ESTIMATES	
a. Baseline	December 17, 1981
b. Revised	May 22, 1981
2. SCHEDULE ACCOMPLISHMENT REPORT	December 17, 1980 January 14, 1981 February 16, 1981 March 16, 1981 April 16, 1981 May 16, 1981
3. PROGRAM PLAN AND WBS	
a. Original	December 17, 1980
b. Revised	May 22, 1980
4. MONTHLY TECHNICAL PROGRESS REPORT	January 15, 1981 February 15, 1981 March 15, 1981 April 15, 1981 May 15, 1981
5. FINANCIAL REPORT	December 15, 1980 January 14, 1981 February 16, 1981 March 16, 1981 April 16, 1981 May 16, 1981
6. DESIGN REVIEW PACKAGE	February 19, 1981
7. QUARTERLY TECHNICAL PROGRESS REPORT	March 15, 1981

G. Activities Planned for Next Quarterly Reporting Period

The third quarter of the Westinghouse MEPSDU program covers the period June 1 through August 31, 1981. The first significant milestone of this quarter is the Module Design Review, scheduled for July 14 at JPL. The Preproduction Module Engineering and Manufacturing Documentation Package, including all drawings and a module manufacturing flow chart, will be submitted to JPL in late June.

Aside from module design work, engineering work will be directed to completing process sequence design and MEPSDU equipment specification work. Vendor contacts will continue through the upcoming quarter.

Preliminary SAMICS costing work will be completed with the submission of a topical report in June which will present results and contain a detailed description of the Format A input data.

Work on the Kulicke and Soffa subcontract in the third quarter of the project will continue on machine concepts. Layouts on individual stations will proceed. Work in the control system area will focus on determining the components to be used for controlling the automated functions of the machine. Investigation of the hardware and software requirements of the machine to be developed and built will proceed, and decisions will be made on procurement of specialized items to be used, depending upon lead times for these components.